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A review of frosting in air-to-air energy exchangers

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A B S T R A C T

Air-to-air heat/energy exchangers are often used with heating or cooling systems in buildings, to transfer heat and moisture from an airstream at a high temperature or humidity to an airstream at a low temperature or humidity. Frosting inside heat/energy exchangers is common in cold regions such as Canada and northern Europe, and results in a significant decrease in the performance of the exchangers. The desire to improve the performance and control strategies of heat/energy exchangers under cold air conditions has led to significant research and development equipment over the past 30 years, however, from an energy savings point of view, this problem has not been researched in as much detail. In this paper, a detailed review of the research on frosting and defrosting techniques, specifically in air-to-air heat/energy exchangers is presented.

Contents

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1. Introduction

Global demands for environmentally clean energy and a shortage of energy resources have led to the development of more energy efficient technologies. In cold countries, 30–50% of the total energy consumed is used for residential and commercial buildings, and 60% of that is dedicated to space heating and cooling [1,2]. Many studies have focused on ways to reduce the amount of energy used by Heating, Ventilation and Air-conditioning (HVAC) systems [2–5,6,7]. Heat/Energy Recovery Ventilators (HRV/ERV) are types of HVAC systems that are designed to reduce energy consumption. An ideal heat/energy exchanger allows sensible and latent (for energy exchangers) heat transfer between supply and exhaust air under all operating conditions without significant cross-contamination. Typical HRV/ERV units contain a heat/energy exchanger, fans, supply and exhaust ducts, air filters, a drainage system and controllers. To design an efficient heat/energy exchanger some factors should be considered such as, pressure drop, fouling, corrosion, maintenance, controls, condensation and frost formation [8].

Frost formation in exchangers is common in cold regions where the outdoor temperature is below -10 °C for the majority of the cold season. Conventional problems created by the formation of frost in energy exchangers are:

- partial or full blockage of air flow passages [9],
- increase in pressure drop through the exchanger or decrease in air flow rate [10–12],
- increase in electric power for the fans [13,14],
- decrease in the heat transfer rate between the two air streams [12] and
- draught in the space due to low supply air temperatures [13].

Additionally, frosting in heat exchangers has been reported as a reason for operational problems in the air conditioning systems of aircraft [10], boats and ships, and electro power systems [15]. Each of the aforementioned problems can result in a reduction in the effectiveness of the equipment over a short time period or physical damage to the equipment over a longer time.

Energy recovery is most beneficial when the outside air is very cold, because high temperature and humidity differences between the indoor and outdoor air creates the potential for high energy transfer rate and energy savings. However, a considerable reduction in the effectiveness of exchangers under frosting conditions reduces energy recovery, exactly when the most energy can potentially be recovered. In this paper, an overview in the open literature in the category of frosting in heat/energy exchangers is presented. Also, a brief review of the process of frost formation and frost properties on simple surfaces is provided. This paper reviews the open literature in the field of frosting in air-to-air heat/energy exchangers, summarizes the findings of previous research, finds similarities and differences in the results, presents defrosting/frost protection techniques or methods to decrease the negative effect of frosting and finally highlights the gaps in the literature.

2. Air-to-air heat/energy exchangers

Energy can be recovered in the form of sensible (heat transfer) or latent (moisture transfer) or both. In air-to-air exchangers two air streams, one is exhaust air from the building and the other is outdoor air (supply air), enter the exchanger core. Depending on the design, energy is transferred directly or indirectly from one air stream to the other. Air-to-air exchangers can be categorized into different groups based on the geometry of the exchanger and the orientation of the airflow. These include fixed plate exchanger, rotary exchanger, run around coils, heat pipe heat exchangers, and twin tower energy recovery loops [8,16], however plate heat/energy exchangers and heat/energy wheels are more widely used, and thus will be the focus of this paper.

2.1. Types of air-to-air heat/energy exchangers

2.1.1. Fixed plate heat/energy exchangers

In this type of exchanger, the supply and exhaust air pass through adjacent channels with parallel surfaces, in counter-flow or cross-flow configurations. If the surfaces are made of an impermeable material (e.g. aluminum or plastic), only heat will transfer between the two streams, while if the surface is a permeable material (e.g. treated paper [17], or a semi-permeable membrane [18,19]) both heat and moisture will transfer between the two streams Fig. 1.

2.1.2. Rotary air-to-air heat/energy exchangers (heat/energy wheels)

A rotary energy exchanger is made of a rotating cylinder, filled with an air-permeable structure with a high surface area in contact with the air. Supply and exhaust air pass through the wheel, in a counter-flow configuration. Heat/moisture are transferred from one air stream to the surface, then the wheel rotates 180° and the heat/moisture from the surface are released in to the other air stream [20] Fig. 2.

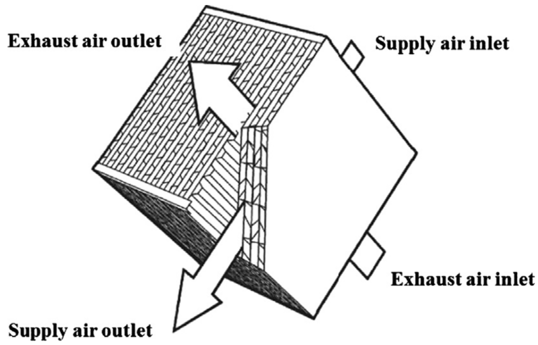

Fig. 1. Fixed-plate cross-flow heat exchanger [8].

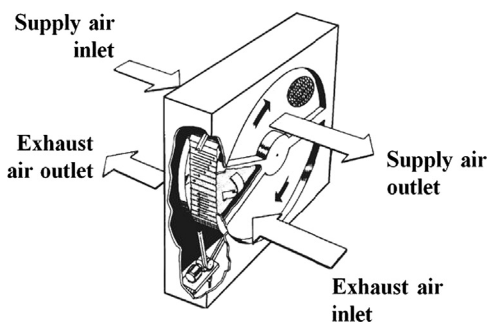

Fig. 2. Rotary air-to-air energy exchanger [8].

2.2. Performance parameters in air-to-air heat/energy exchangers

The performance of air-to-air heat/energy exchangers depends on many factors, including inlet conditions, as well design parameters. The performance of exchangers is quantified using the following parameters:

2.2.1. Effectiveness

The main indicator of performance in air-to-air exchangers is the effectiveness: sensible effectiveness for a heat exchanger and both sensible and latent effectivenesses for a energy exchanger. The effectiveness of an exchanger is calculated for the supply and exhaust streams from the following equations [21]:

$$\varepsilon_{supply} = \frac{q_{actual\_supply}}{q_{max\ imum}} \tag{1}$$

$$\varepsilon_{exhaust} = \frac{q_{actual\_exhaust}}{q_{max\ imum}} \tag{2}$$

where

$$q_{actual\_supply} = D_2(X_1 - X_2)$$
$$q_{actual\_exhaust} = D_3(X_4 - X_3)$$
$$q_{max\ imum} = D_{min}(X_1 - X_3) \tag{3}$$

The indices represent (1) supply inlet, (2) supply outlet, (3) exhaust inlet and (4) exhaust outlet of the exchanger. In the above equation X is the dry-bulb temperature (T) for calculating sensible effectiveness, the humidity ratio (W) for calculating latent effectiveness or the enthalpy (h) for calculating total effectiveness. The variable D is replaced by

$\dot{m}C_p$ for sensible effectiveness
$\dot{m}h_{fg}$ for latent effectiveness
$\dot{m}$ for total effectiveness

where $\dot{m}$ is the mass flow rate of the dry air, C_p is the specific heat of dry air, and h_{fg} is the heat of vaporization of water. When no frost, condensation or excessive moisture transfer is present in the exchanger, the effectivenesses on the supply and exhaust sides should be the same.

2.2.2. Outdoor Air Correction Factor (OACF)

The outdoor air correction factor is a measure of the leakage between the supply duct and the exhaust duct in an exchanger. If there is no leakage, the value will be one. The outdoor air correction factor is calculated from [21]

$$OACF = \frac{\dot{m}_1}{\dot{m}_2} \tag{4}$$

2.2.3. Exhaust air transfer ratio

The exhaust air transfer ratio is a scale indicating the amount of leakage of a specific gas from one side to the other defined by [21]

$$EATR = \frac{C_2 - C_1}{C_3 - C_1} \tag{5}$$

where C is the tracer gas concentration at each location.

2.2.4. Recovery Efficiency Ratio (RER)

The recovery efficiency ratio is a ratio of the energy transferred in the energy exchanger to the energy consumed by the exchanger. It defines by [21]

$$RER = \frac{\dot{m}_2(h_1 - h_2)}{(\Delta p_S Q_2/\eta_{fs} + \Delta p_E Q_3/\eta_{fe} + q_{aux})} \tag{6}$$

Δp_S and Δp_S are the pressure drop across the supply and exhaust side of the exchanger respectively. Q is the volume flow rate, η_{fs} and η_{fe} are the supply and exhaust side fan efficiencies, q_{aux} the auxiliary total power input.

In addition to these performance parameters, some important non-dimensional parameters that are used to define exchangers are [22]

Number of heat transfer units (NTU)

$$NTU = \frac{UA}{C_{min}} \tag{7}$$

And capacity ratio

$$c_r = \frac{C_{min}}{C_{max}} \tag{8}$$

where U is the overall convective heat transfer coefficient, A is the heat transfer area associated with U, and C_{min} and C_{max} is the minimum and maximum heat capacity between warm ($C_h = (\dot{m}c_p)_h$) and cold ($C_c = (\dot{m}c_p)_c$) fluid capacity rate respectively.

Sensible effectiveness (ε_s) can be expressed as a function of NTU and c_r [22]:

$$\varepsilon_s = f(NTU, c_r, Flow\ arrangement) \tag{9}$$

It can be understood from Eq. (9) that effectiveness is independent of exchanger inlet temperatures. The functional relationships in Eq. (9) are provided in [22] and other heat transfer books for different flow arrangements.

For energy exchangers mass transfer occurs as well as heat transfer. The number of mass transfer units (NTU_m) in energy exchangers NTU_m is defined by [23]

$$NTU_m = \frac{U_m A}{\dot{m}_{min}} \tag{10}$$

where U_m is the overall convective mass transfer coefficient, and $\dot{m}_{min}$ is the minimum mass flow rate between the two air streams.

3. Overview of research on frosting in heat/energy exchangers

In order to provide a review of the current literature on frosting in heat and energy exchangers, a search was performed using an

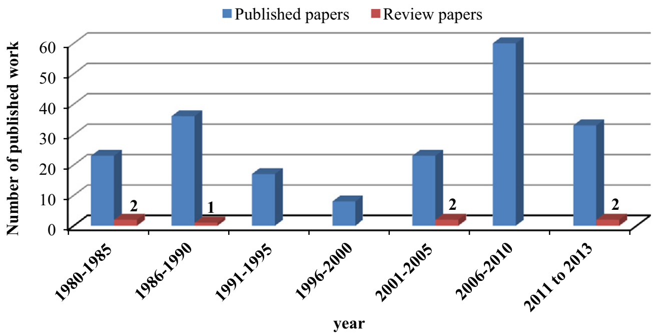

Fig. 3. Distribution of the published work from 1980–2013 on frosting in heat/energy exchangers.

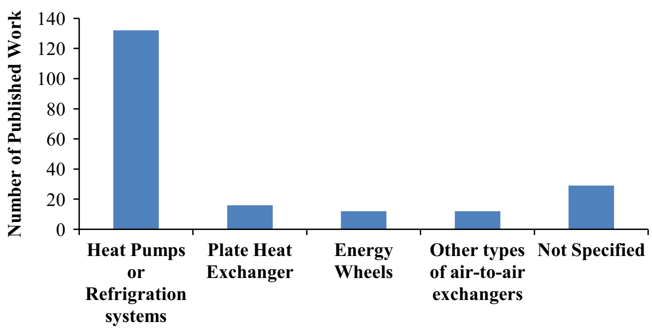

Fig. 4. Distribution of the published work from 1980–2013 based on the type of heat/energy exchanger.

inclusive engineering publication database.[1] Fig. 3 shows the number of papers published, over five years periods, from 1980 to 2013 related to frost in heat and energy exchangers. It can be seen that frosting in heat/energy exchangers has been a concern for the past 30 years, but has received more attention in the last decade. By categorizing the studies based on the type of heat/energy exchangers in Fig. 4, it can be seen that most of the research has been on heat pumps and refrigeration systems, and very little research has focused on air-to-air heat/energy exchangers. There are fewer papers on other types of air-to-air exchangers in applications such as electronic device, cars or aircrafts. The remaining papers are grouped in the "not specified" category because the research was on simple geometries such as frosting on plates or tubes or the application was not clear from the abstract. Considering only the review papers in frosting in heat/energy exchangers in Fig. 3 showed that no comprehensive review for frosting in air-to-air heat/energy exchangers. Most of reviews are in frosting in heat pumps, or frost properties. This review paper will focus on those papers relating to plate heat exchangers and energy wheels. These devices are described in the next section.

Since both heat and energy exchangers are considered in this review, it is also interesting to look at the distribution of papers by the type of energy transfer. As depicted in Fig. 5, most of the papers have included sensible heat transfer only, while a smaller amount have considered latent heat transfer or mass transfer in the exchangers as well. Fig. 6 shows that the majority of the published works have reported frosting issues in exchangers, while a lower number have considered or investigated frost protection techniques and methods of defrosting the exchangers.

Although, the concept of frost formation in exchangers has received increasing interest from researchers and industry over

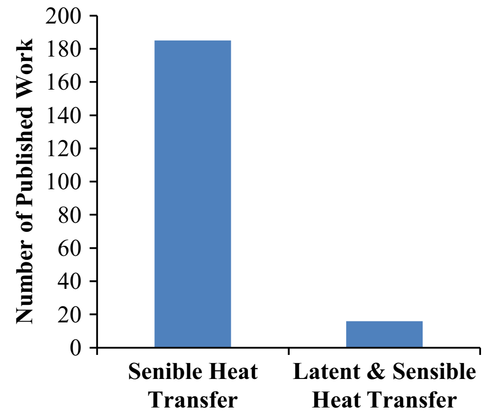

Fig. 5. Distribution of the published work from 1980–2013 based on the energy transfer method.

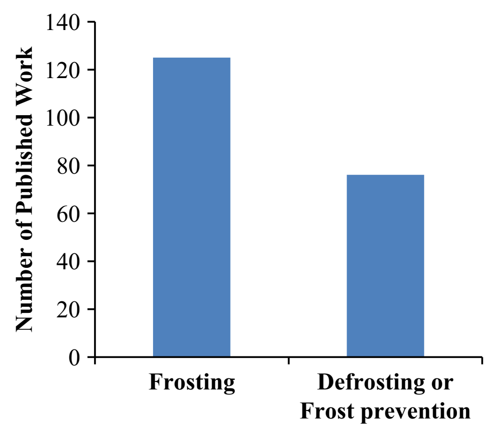

Fig. 6. Distribution of the published work from 1980–2013 based on the content of the research.

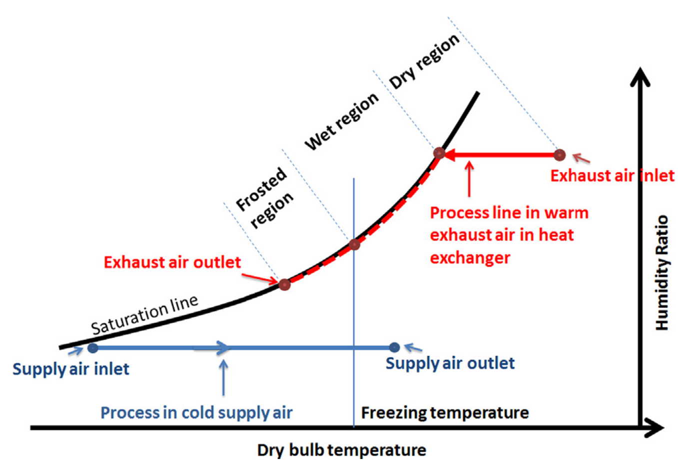

Fig. 7. Psychometric chart showing the processes in the exhaust and supply air streams in heat exchangers.

the past 30 years, this problem is still unresolved and specifically, more work is needed to study frost in exchangers which transfer latent heat as well as sensible heat. In addition, more research is required to find new defrosting techniques or frost prevention methods. In recent years, new types of porous materials – called semi-permeable membranes – which can transfer moisture as well as heat have been developed and have applications in both air-to-air and air-to-liquid energy exchangers [18]. However, the search

[1] www.engineeringvillage.com.

for papers on frosting in energy exchangers produced no papers that studied frosting in membrane based energy exchangers.

4. Frosting in exchangers

Frosting in heat and energy exchangers is observed when the outdoor temperature falls below the frosting threshold of the equipment at certain relative humidity (RH) levels [24]. In addition to the outside temperature and humidity ratio, the frosting limit (the lowest outdoor air temperature which does not lead to frosting in the exchanger) for each exchanger is strongly dependent on its design and the type of energy transfer (sensible or latent). Typically, frosting will be observed for outdoor temperatures below −5 °C, if no frost protection techniques are implemented. In a mild climate, frost protection techniques have little impact on the performance of the exchangers, while in cold regions those techniques are important [24]. In the following subsections, the process of frost formation is explained and different studies on frosting in exchangers are described.

4.1. Physical process of frost formation in heat/energy exchangers

When warm moist air (exhaust air) passes over a surface with a low temperature, part of its energy in the form of sensible heat is transferred to the surface. If the temperature of the exhaust air goes below the dew point temperature, moisture will condense on the surface. If the surface temperature is lower than the freezing point of water, frosting will occur. This process is shown in Fig. 7.

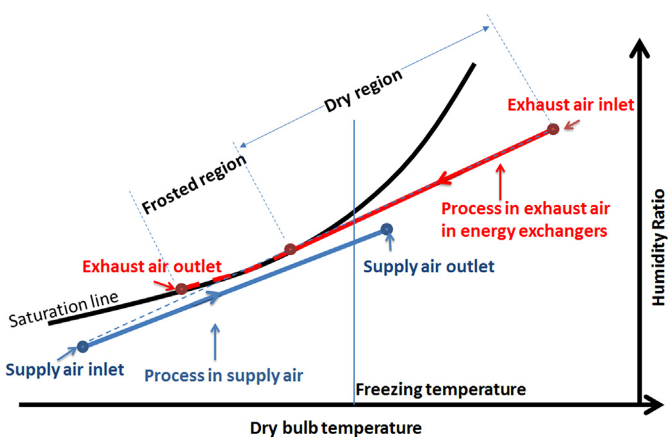

Fig. 8. Psychometric chart showing the processes in the exhaust and supply air streams in energy exchangers.

From this figure, it can be seen that condensation and frosting may occur in the exhaust side of a heat exchanger.

In total energy exchangers, such as energy wheels or membrane exchangers, in which both latent and sensible heat can be transferred, a different process happens on the psychometric chart. As shown in Fig. 8, the exhaust air temperature and humidity ratio decrease simultaneously. In this situation. Therefore, exhaust air can reach a temperature below the freezing point before frosting is observed. The addition of moisture transfer results in a decrease in the humidity ratio and dew point temperature of the exhaust air, as the air moves towards the outlet. A rule of thumb predicts saturation conditions in an energy exchanger when a straight line connecting the inlet supply and exhaust conditions on the psychometric chart touches the saturation line [25]. If the contacting point is below the freezing temperature (similar to Fig. 8), frosting in the exchanger may occur.

Based on the description of the frosting process, it can be concluded that the main factors that lead to frosting are high air humidity ratios and low surface temperatures inside the exchanger. In addition to the type of exchanger, the rate of frost-buildup is dependent on the air conditions, the surface temperature and the water vapor permeability of the surface. The reviewed literature on frosting in heat/energy exchangers can be classified into three main categories:

- measurement of frost properties such as density, porosity, growth rate, conductivity and thermal heat transfer coefficient,
- frost formation on heat exchanger surfaces and the effect of frost on the performance of the equipment (exchanger effectiveness, pressure drop, and flow rate) without any defrost cycle and
- development of defrosting techniques for heat exchangers and investigating the effects of those techniques on the performance of an exchanger.

5. Research on frost properties

To be able to analyze the effects of frost formation on exchangers, the properties of frost should be taken into consideration. These properties include frost growth rate, structure, density, thermal conductivity, and roughness. Some review papers have been published in this area [26,27]. The aim of this section is to present key results of research on frost properties which will help the reader understand frost growth which is necessary to predict the effects of frosting in energy exchangers.

5.1. Frost formation, structure and location on simple geometries

Formation of frost is an unsteady process with different steps. The difference between each step is related to the structure of the frost.

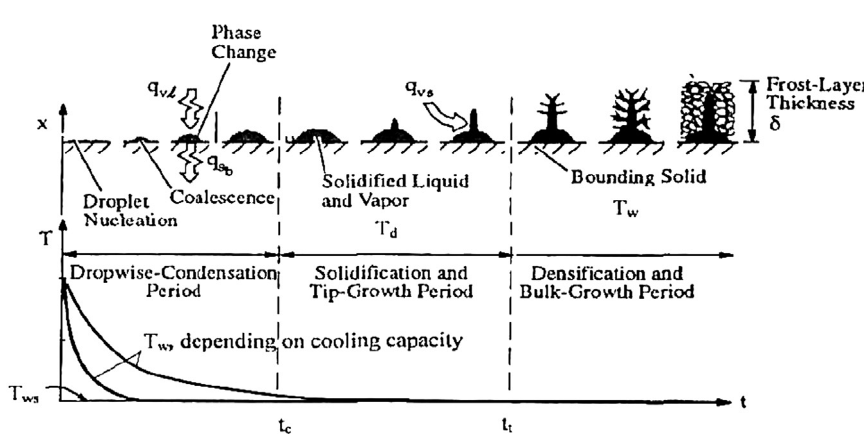

Fig. 9. Frost growth process with time [26]. *t* is time and *T* is the cold wall surface temperature.

Iragory [26] defined these steps as: Dropwise Condensation Period (DWP) or Nucleation, Tip-Growth Period (TGP) or frost formation, and densification and Bulk-Growth (DBG) or frost layer which is shown in Fig. 9. Mao [28] experimentally monitored the process on a flat plate in which a laser beam was used to measure the frost thickness. Melting of the upper layer of frost and the penetration of liquid in to the lower layers changed the frost layer into ice. Important parameters affecting frost growth on the surface of a heat exchanger were shown to be the air velocity and temperature, plate temperature, humidity ratio of the air, and properties of the surface [29].

Since frost formation is a transient process, the temperature of the frost layer in contact with the air varies with time, which results in different structures within the frost layer. This inhomogeneous structure makes it difficult to find a general equation or correlation to predict frost properties. Knowledge of the frost thickness on a flat plate is required to calculate the pressure drop or mean velocity over a surface. Frost thickness was found to be linearly related to the air humidity by O'Neal and Tree [29], while Fisk et al. [11] found a non-linear relation between those frost thickness and humidity. Fisk et al. [11] proposed that heat release during condensation in heat exchangers also played an important role on frost growth and caused the non-linear relationship. A comprehensive review of the studies on frost properties over the 50 years before 1985 is provided by O'Neal and Tree [29]. They found that the structure of frost can be considerably different on a plate with a temperature of $-5\,^{\circ}\mathrm{C}$ compared to $-30\,^{\circ}\mathrm{C}$. Also, the frost growth process on simple geometries such flat plate, cylinder, parallel plates, and annuli were compared together. The location of thick frost layer on a isothermal flat surface was found to be very dependent on the airflow rates, while in a channel with parallel plates with constant temperature, frosting was observed to be independent of the air flow rate for air velocities higher than 8–10 m/s.

In addition to the experimental work, researchers have tried to create theoretical models to predict frost properties. Padki et al. [30] used a numerical method to find frost thickness, its rate of growth, and the temperature distribution along a frosted surface with a flat plate and cylindrical plate geometry. To simplify the model, they utilized correlations for the heat transfer coefficient on similar geometries without frosting. The results were in agreement with the experiments in the literature, however their model was one-dimensional and no-blockage or pressure drop were considered. Thus, their findings are not applicable in the geometries in which partial blockage by frost is considerable. The same problem was observed in numerical results by Chen [31] on finned surfaces and Mercadier [36] for counter-flow heat exchangers. In [32] the effect of frost on pressure drop was found to be eight times higher than the effect on the heat transfer rate. Pressure drop was described to be more reliable than the measurement of the heat transfer coefficient in determining the effect of frosting on the performance of air finned coil. It is difficult to develop numerical models and correlations for frost growth on a surface due to:

- the change in frost properties with time and location on the surface,
- the continuous change in the frost-air interface temperature and
- alternating melting and freezing processes in the frost layer when the frost-air interface temperature is changing.

5.2. Frost density, thermal conductivity and heat transfer coefficient

Iragorry et al. [26] categorized findings of the studies on frost properties into thermal conductivity, average density, frost thickness and the frost-to-air heat transfer coefficient. Frost density is in direct relation to conductivity. In addition to the frost density, the grain size and flow path length (or tortuosity) were also found to affect the conductivity. When the temperature difference between the air and the plate was large, the density of the frost was found to be lower than when the temperature difference was small. Thus, the density of the frost found in heat exchangers is expected to be low, since the temperature difference is usually high. Also, low conductivity is a result of low density frost which has a large impact on effectiveness. The air velocity and the orientation of the plates are other factors that affect the density of the frost [26].

The roughness of a surface plays an important role in heat transfer from the surface, especially in transitional and turbulent flow regimes [27]. Due to the high surface roughness of a frost layer, the frost-to-air heat transfer coefficient (outside the laminar flow regime) is higher than under the same conditions for a surface without frost [29]. It is difficult to measure the roughness of frost, and only very limited studies were reported in [27]. In most correlations found in the literature, the heat transfer coefficient of a frosted surface is assumed to be the same as a non-frosted surface. Although, in laminar and transitional flows this assumption may be correct, in turbulent flows the frost roughness will have an effect on the heat transfer coefficient.

5.3. Frost on extended surfaces

For exchangers with extended surfaces such as finned heat exchangers, more variables contribute to the performance of the exchanger. Kondepudi and O'Neal [27] reviewed the research on extended surfaces (mostly theoretical), and categorized the research findings into four group: fin efficiency, total heat transfer coefficient, pressure drop, and surface roughness under frost formation. It was reported that 1–3 mm of frost reduced the fin efficiency up to 20%. However, fin efficiency increased at the initial stage of frosting due to an increase in the surface roughness and air velocity passing over the fins. The rate of frost growth on finned surfaces was measured using a laser beam by Thomas [33], and the results were used to validate a numerical model by Chen [31,32]. A one-dimensional porous structure was considered for the frost layer by Chen but the model lacked proper prediction of the pressure drop when the blockage by the frost was large. Indeed, a very small change in the frost thickness resulted in a high change in the pressure drop and that made the validation of the theoretical and numerical results difficult.

5.4. Frost deposition pattern

Frosting is inevitable in many systems. Thus, some researchers have tried to control the distribution of frost. An uneven temperature distribution along the fin surface in heat exchangers can have some effect on frost growth. Wu et al. [34] investigated parameters that have more effects on the frost deposition pattern (FDP) to find a way to produce uniform frost formation on the air side surface of a plain-fin-tube evaporator to retard blockage of the airflow path. They found FDP was dependent on air velocity, humidity and surface temperature (dependent on air and refrigerant temperature and refrigerant flow rate), and concluded that equal FDP on all of the rows was possible. To explore more details of FDP, Gao and Gong [35] tried to model frosting on the same type of exchanger. Their results confirmed that the temperature difference between the air and the surface has more effect on frosting than the humidity. Padhmanabhan et al. [36] found that ignoring uneven frost growth resulted in 20–50% error in predicting frost thickness and 40% error in coil heat transfer capacity. They developed a semi-empirical frost model to simulate non-uniformities in FDPIn addition to temperature, humidity and flow rate of air, Padhmanabhan et al. studied air flow patterns. They found that ignoring the flow pattern produced a large error in predicting the frost

thickness and coil capacity. Although, some improvement is still required, their model is considered one of the most accurate models for predicting frosting in fin-tube heat exchangers.

5.5. Summary

In the literature presented in this section, the research has mainly focused on understanding the process of frost formation on simple geometries and calculating or predicting frost properties. The literature can be summarized as follows:

- The important frost properties are thermal conductivity, average density, thickness, and heat transfer coefficient.
- The surface and air temperature, air humidity, flow rate, and surface geometry affect the frosting rate.
- Frosting has a greater effect on pressure drop than on the heat transfer rate.
- Uneven frost deposition may cause considerable error in numerical results.
- The transient process of frosting (which contains freezing and melting), and its inhomogeneous structure make it difficult to develop accurate frosting models.

These findings are useful for prediction of heat transfer in more complicated geometries, where frost formation and direct measurement of its properties are not feasible. One of those conditions happens when frost is forming in heat or energy exchangers. In the following sections published work on the field of frosting in air-to-air heat and energy exchangers are reviewed.

6. Air-to-air heat exchangers

Because of their simplicity in design, heat exchangers are used more than energy exchangers in heating systems of buildings. Researchers have tried to measure different aspects of the effects of frosting in heat exchangers, such as the location of frost growth in exchangers, how frost affects the performance (including effectiveness, pressure drop and the rate of change in those parameters by time), and frosting thresholds for when frost occurs. This section will review the literature on frosting in air-to-air heat exchangers and the following section will review the literature on frosting in all other energy exchangers.

6.1. Frost deposition pattern in exchangers

Bantle et al. [9,37] presented the first one-dimensional mathematical model for frost in a counter-flow plate heat exchanger by using empirical correlations. Although, the numerical and experimental heat transfer rate and temperature results had the same trend, differences between the values were considerable. Non-uniform frost formation inside the exhaust air channels was suspected to be the main reason for disagreement of the numerical results with the experiments. Fig. 10 shows stream lines they calculated for the case of negligible entrance effect. Exhaust air particles on streamline ψ_1 follow a longer path (and time) compared to particles on other streamlines (ψ_2 and ψ_3), and are expected to experience a greater temperature reduction. Therefore, frosting in the particles on ψ_1 will happen sooner than on other streamlines resulting in non-uniform frost deposition. This non-uniformity and blockage of the air channels near the supply air inlet, turns the streamlines in to three dimensional patterns. One very difficult part in modeling exchangers under frosting is dealing with this non-uniformity.

Although counter-flow heat exchangers usually have a higher effectiveness compared to cross-flow exchangers, the construction and header design of the latter is simpler. In addition, full blockage of exhaust air due to frosting is less likely to happen in the cross-flow configuration. The typical distribution of different regions in these exchangers under frosting is shown in Fig. 11. The frosting threshold in cross-flow exchangers is typically at temperatures below −5 °C [38].

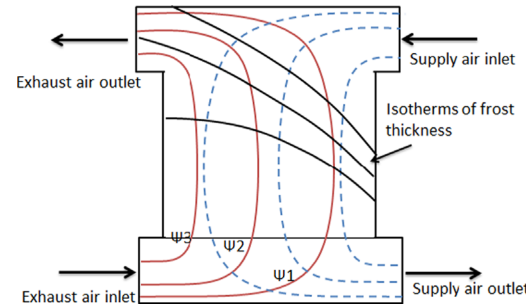

Fig. 10. Streamlines of flow configuration in cross counter-flow heat exchanger under laminar flow regime [9].

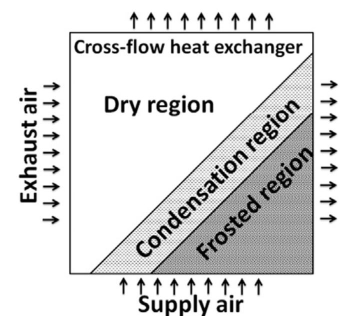

Fig. 11. Different regions in a typical cross-flow heat exchanger under frosting [39].

6.2. Effectiveness of heat exchangers under frosting

If no condensation or frosting happens in an exchanger and the change in air properties are not significant, the effectiveness of an exchanger is independent of the inlet air properties [6]. Otherwise, frosting affects the efficiency of the HRV or effectiveness of the exchanger. For example, an increase in the pressure drop or decrease in flow rate through an exchanger, caused by frosting, changes the working point of the fan delivering the airflow, which reduces the performance of the fan. Also, the layer of frost decreases heat transfer between two air streams by increasing the thermal resistance of the separating walls or reduces the heat transfer coefficient due to a reduction in the flow rate.

The change in the effectiveness with time, under frosting conditions, in a plate heat exchanger was calculated by Phillips et al. [40]. Results showed that an exchanger with a high effectiveness frosted at a higher temperature than an exchanger with a lower effectiveness. But this conclusion was not in agreement for the results by Holmberg [41]. He numerically modeled two types of cross-flow plate heat exchangers, single-pass and double-pass, under steady state conditions (Fig. 12). As expected the sensible effectiveness was higher for the double-pass heat exchanger [2]. But, the frosting limit was lower for latter exchanger. Holmberg also found that the sensible effectiveness increased with RH or temperature of the warm air, or a reduction in the cold air temperature. Although, condensation increased the sensible effectiveness, higher condensation resulted in more frost eventually. Holmberg's steady state model did not include frost growth or its effect on the exchanger's pressure drop and flow rate. Thus, the results of this study are relevant only when no frost is observed. A

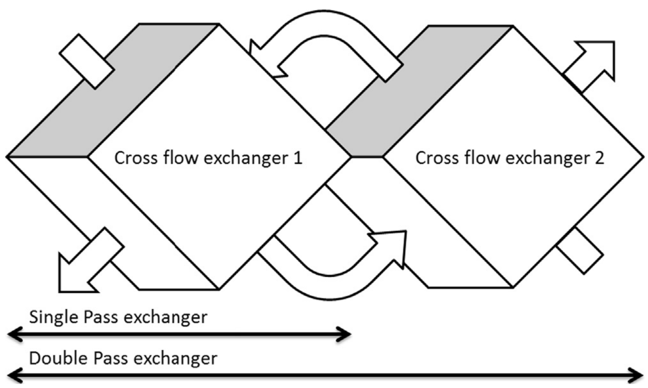

Fig. 12. Double-pass heat exchanger [41].

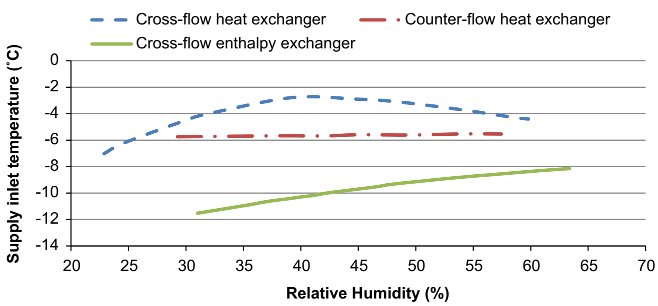

Fig. 13. Experimental results on frosting limit for three types of exchangers [11].

similar problem was observed in the numerical results by Mercadier et al. [39] compare to experiments when partial blockage happened in the exchanger. They modeled a plate heat exchanger considering unsteady conditions. After 40 min of operating under −25 °C, more than half of the channels near the exhaust inlet were blocked leading to a rapid drop in the effectiveness. They found that the rate of change in the effectiveness and the outlet temperatures were very high in the first five minutes of operating the exchanger and after that, the rate of change remained constant. These results were in agreement with experiments.

Phillips et al. [40] used a computer program to model a counter-flow air-to-air plate heat exchanger under frosting conditions. Three similar exchangers with different effectivenesses, 50%, 65% and 85% were modeled under supply temperatures of −20 °C and −40 °C. Changes in effectiveness and air stream temperatures with time were calculated. Results showed that a higher effectiveness lead to faster frosting and channel blockage. For the exchanger with 50% effectiveness, steady state conditions were reached after a specific amount of reduction in the effectiveness due to frosting. In the exchanger with 65% effectiveness, steady state conditions were not met after 24 h and for the exchanger with 85% effectiveness, complete blockage happened before 15 h. Thus, exchangers with lower effectiveness will have less working problems under frosting conditions. A lack of empirical correlations for frosting and no experimental data to validate the results were the main limitations of this work.

6.3. Frost location

Condensation, frosting and melting in a counter-flow air-to-air heat exchanger was modeled numerically with Simulink and the results were compared with experimental data by Nielsen et al. [42]. It was found that frost forms closer to the exhaust air outlet. This result was also found by Holmberg in cross-flow heat exchangers [41] and Simonson et al. [43] for energy wheels. Unlike in the work in [41–43], Mercadier et al. [39] found that the rate of frost growth was higher near the exhaust air inlet than other parts of air channels, and partial air channel blockage was observed near the exhaust inlet. This difference shows the dependency of the frost location to the design and air properties, and no clear conclusion can be extracted.

6.4. Summary

Based on the literature reviewed in Section 6, the following conclusions can be made:

- a lack of experimental data and non-uniformities in frost deposition patterns are the main challenges in presenting accurate numerical models,
- three dimensional flow pattern in cross-flow heat exchangers make it more difficult to model frosting compared to counter-flow exchangers,
- cross-flow heat exchangers are preferred for cold regions because they have less blockage problem,
- exchangers with lower effectivenesses have a lower frosting limit,
- the location of frost growth in the exhaust side may vary depending on the test conditions.

7. Air-to-air energy exchangers

As described in the introduction, heat and moisture are simultaneously transferred between two air streams in an energy exchanger. A review has been done by Alonso et al. [44] for different types of air-to-air exchangers to be used in cold regions. Results showed that energy exchangers have less risk of frosting in cold climates. Considering both IAQ and frosting problem, the best recommendation for cold regions was to use recuperative energy exchangers. However, further investigation did not reveal more studies to consider recuperative energy exchangers such as membrane based exchanger under frosting.

A design comparison of different types of energy exchangers has been provided in [17,45]. In [45] the effects of heat and moisture recovery on space conditioning load and indoor air quality of residential houses, for three different weather conditions (very cold and dry, cold and humid, and warm and humid) were modeled. It was found that heat and moisture recovery was required for very cold and dry regions, to reduce the conditioning load and keep the indoor air quality at suitable conditions, while moisture recovery was not recommended in warm and humid regions. From this study, it can be concluded that energy exchangers have two benefits over heat exchangers in very cold and dry regions; a reduction in conditioning load and a lower frosting limit.

7.1. Frosting limit

Two common types of energy exchangers are energy wheels and porous plate enthalpy exchangers. Porous plate enthalpy exchangers, as described in [17] have a similar design to plate heat exchangers, but incorporate treated paper with a high moisture permeability instead of an impermeable plate. This type of paper core was not recommended when condensation occurred on the surface. The frosting limit, temperature at which frosting was observed, of plate enthalpy exchangers, using a treated paper core for moisture transfer was found to be approximately 5 °C less than similar plate heat exchangers [11,17]. However, this type of exchanger is not widely used.

One of the first comparisons between air-to-air heat and energy exchangers was reported by Fisk et al. [11], in which three

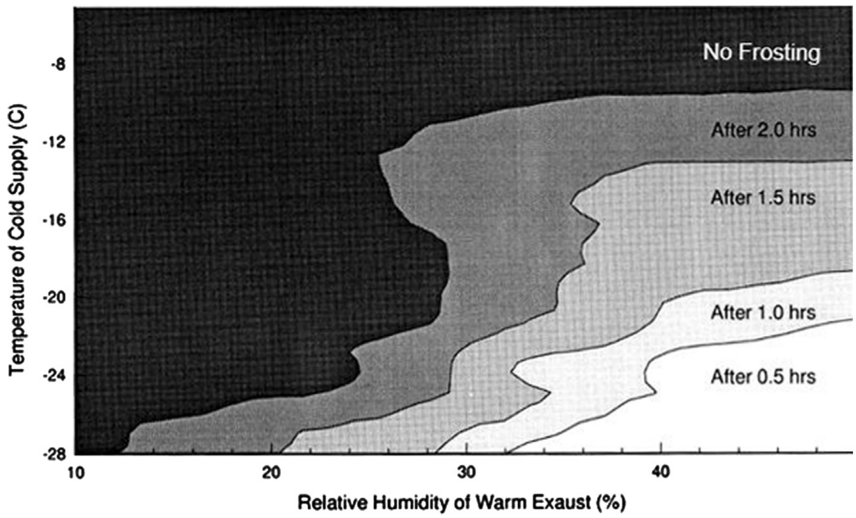

Fig. 14. Frosting limit in an energy wheel with an exhaust air inlet of 22 °C K and different humilities at different supply air temperature and a humidity ratio of 0.23 g_w/kg_a [48].

types of heat and energy exchangers were tested under equal cold supply air conditions to find the frosting limit of each exchanger. The three exchangers consisted of a cross-flow heat exchanger, a counter-flow heat exchanger, and a cross-flow enthalpy type (paper based) exchanger. This study was the only work found in which an enthalpy-type plate exchanger was tested under frosting conditions. The test was conducted for six hours. Fisk et al. used a visual technique to monitor frost formation and the pressure drop across the exchanger. The visual monitoring allowed for earlier frost detection than the pressure drop measurements. The frosting limit for the enthalpy exchanger was found to be lower than the frosting limit for the two heat exchangers (Fig. 13), due to the moisture transfer from exhaust air to supply air. Interestingly, as the RH increased, the frosting limit first increased and then decreased in the cross-flow heat exchanger, while in the counter-flow heat exchanger, the frosting limit was independent of RH. The researchers related the trend in the cross-flow heat exchanger to the condensation heat release when the RH increased. The results of Fisk et al. [11] were in agreement with Holmberg [41] who compared the frosting limits of one-core and double-core heat exchangers. Due to higher condensation in the double-core exchanger, the frosting limit was lower for the double-core exchanger.

The frosting limit in energy wheels is dependent on air properties, design and material, so a typical value is difficult to find as it varies from one energy wheel to the next. It can be concluded from the literature, however, that the frosting limit in energy wheels is generally 5–15 °C lower than typical heat exchangers [17,45–47]. For example in [25], the frosting limit of a hygroscopic wheel was found to be approximately 10 °C less than for a non-hygroscopic surface. Simonson and Besant [43] found that the frosting limit of an energy wheel is dependent on the type of desiccant coating used on the energy wheel surface. Under similar exhaust air conditions, condensation occurred at a higher temperature when a desiccant coating with a non-linear sorption isotherm was used, as compared to a desiccant coating with a linear sorption isotherm.

Bilodeau et al. [48] determined the time for frosting to occur on an energy wheel, under different exhaust humidities and supply air temperatures, as shown in Fig. 14. The results revealed that the frosting limit varies nonlinearly with temperature and RH. The dark region in this figure represents the conditions with no frosting. It can be concluded that frost control strategies based on fixed temperature and humidity values are not reliable [48].

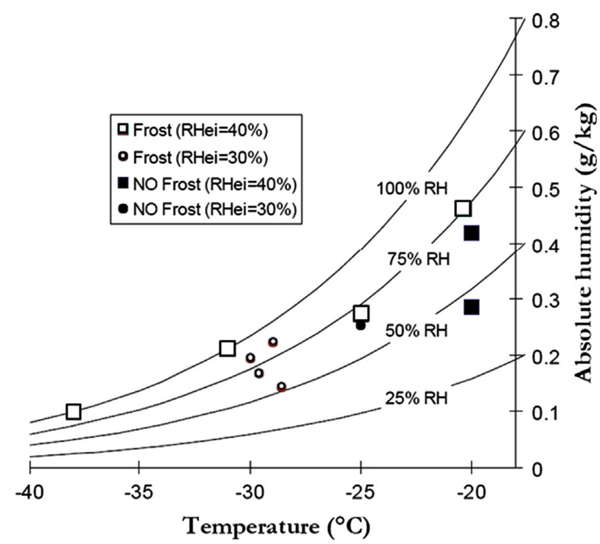

Fig. 15. Results of frosting limits in an energy wheel for different exhaust air relative humidities [50].

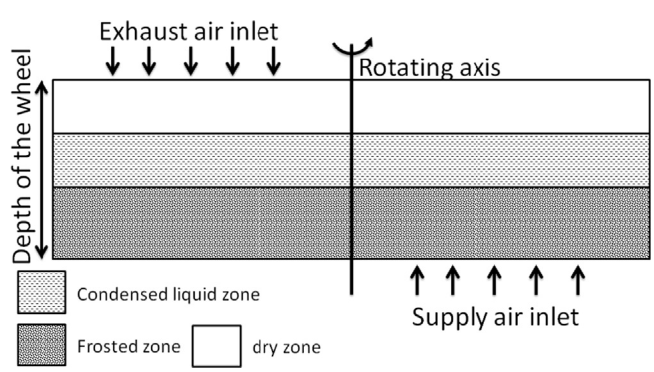

Fig. 16. Different regions in a cross view of the energy wheel with frosting [25].

Theoretical analysis of frosting in exchangers with acceptable uncertainty is very difficult and requires a great range of assumptions. Therefore, laboratory and field tests are required to find frosting limits and the possible change in the performance of an exchanger due to frosting [49]. Gazi and Simonson [50] tested an energy wheel under supply temperatures of −20 °C to −40 °C

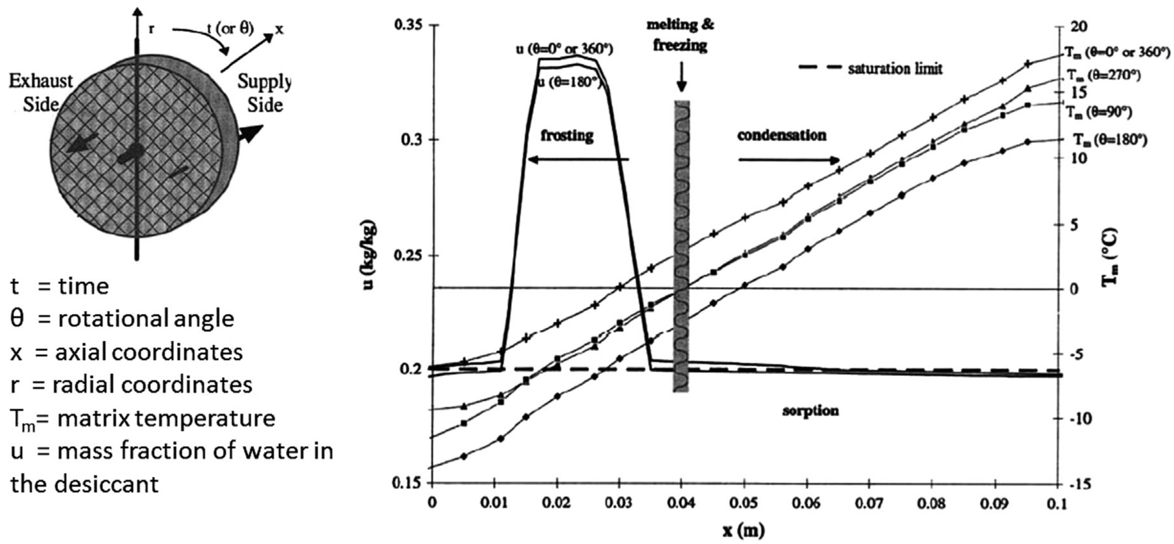

Fig. 17. Moisture content and frost formation across air tubes in energy wheel [43].

when indoor conditions were 22 °C and 30% and 40% RH. For an indoor humidity of 30% RH and a supply air temperature of −29 °C frosting was observed, while with an indoor humidity of 40% RH, the onset of frosting was observed at −20 °C (Fig. 15). This result was consistent with those in [43] where frosting was predicted for RH values higher than 35% RH with supply air temperatures below −20 °C. This shows the high dependence of the onset of frosting on the RH of the exhaust air stream. Thus, using energy exchangers with high latent effectivenesses would decrease the risk of frost formation considerably. It should be mentioned that using liquid nitrogen to provide the low supply air temperature in these tests made it difficult to perform the test for a long time.

7.2. Frost type and location

Knowing the area in an energy exchanger where most of the frost may form is important as it helps engineers to develop or use efficient frost protection techniques. To predict the location of frost formation, the possible types of frost and required air conditions should be calculated. However, similar to what was found for heat exchangers, there is no general agreement for the location of frost formation in the literature. Ruth et al. [47] described two types of frosting processes; direct vapor frosting, and vapor to liquid frosting. Observation of each of these processes was dependent on the matrix temperature and triple point of the vapor. If the matrix temperature is above the triple point, the vapor first condenses as liquid, while for temperatures lower than the triple point, the vapor would condense as a solid phase.

In addition to the frosting processes, two different types of frost were observed by Bilodeau et al. [48]: rough frost and glazed frost. Rough frost occurs when the gradients of temperature and mass transfer are high. Rough frost grows rapidly and as a result, has a lower conductivity and density than the glazed frost. Experiments showed that the possibility of glazed frost forming in rotary exchangers in cold climates was less likely.

Holmberg [25] related the formation of frost to the temperature and showed the distribution of frosted and non-frosted regions as depicted in Fig. 16. Similarly, Bilodeau [48] mentioned that the formation of frost is more likely at the exhaust air outlet, where the matrix has the lowest temperature. However, as described previously, frosting is also dependent on the rate of condensation or adsorption, and the coldest point in the exchanger is not always the same as the point with highest condensation or adsorption rate. For this reason, other researchers found different frost

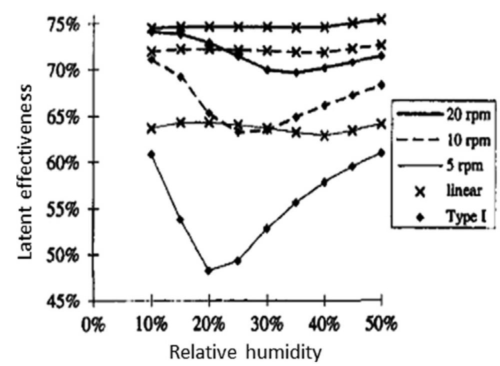

Fig. 18. Latent effectiveness of an energy wheel for different relative humidity values with a supply air temperature of −20 °C for two different desiccant coatings [43].

distribution zones. In [51], it was observed that at the early stage, frost thickness increased faster in the middle of the wheel, and similar to what was found from the numerical model in [43] the frost thickness was higher in that area.

In Fig. 17, the matrix temperature at different rotational angles and radial locations are shown, to demonstrate at what locations condensation and frosting/melting are more likely. Matrix temperature and moisture content across the air channels at different angles is shown in the graph. At steady state conditions, the entire matrix tube would contain three zones, a frosted section, a section with liquid water and a section where condensation or adsorption-desorption happens periodically. However, in the extreme cold supply air, no steady conditions would be observed and frost accumulation in the tubes results in the full blockage of the air passage.

7.3. Impact of frosting on effectiveness

In addition to experimental work, Bilodeau et al. [48] also numerically modeled an energy wheel with frost formation using three-dimensional equations. They found that reducing the mass flow rate of the air or increasing the wheel thickness decreased the formation of frost, and gradually increase enthalpic effectiveness. The reason for this is that a thicker wheel augments heat transfer as well as mass transfer and reduces frost formation. Bilodeau et al. found that a high exhaust air RH increased the matrix temperature, which also reduced frost formation. Simulation

results in [43] indicated that a desiccant with linear sorption isotherms provided higher total effectiveness and less condensation and frosting under similar conditions to that of a desiccant with type I isotherms described previously. As depicted in Fig. 18 latent effectiveness changes non-linearly with RH for both types of desiccants. Due to higher effectiveness values and less sensitivity to the RH of the exhaust air, wheels with a desiccant coating that has a linear isotherm are more preferable for cold regions.

Observation and measurement of frost properties inside the air channels of exchangers is difficult, so most researchers use numerical modeling to determine the properties of frost. Shang et al. [51] used one-dimensional equations for heat and mass transfer in porous media to develop a numerical model to predict the frost properties in an air channel of a desiccant coated energy wheel when the supply air temperature was $-40\,^{\circ}$C. In Shang's model, just one air stream was solved, as shown in Fig. 19. They reported variations in the pressure drop in 1–2 min cycles due to frost formation and frost fracture by fatigue phenomena. The numerical results showed large variations in temperature at the frost-air interface. As the frost fracture was not modeled directly, frost formation was modeled in two separate cases; before the first fracture and after several fractures. Their results showed a gradual increase in the frost thickness and average density of the frost with time, which is in agreement with the literature. Shang et al. found that the sensible effectiveness of the energy wheel decreased with time when frosting occurred in the exchanger. The experiments done by Gazi and Simonson [50], however, showed that the effectiveness of an energy wheel increased when frosting occurred. They related this increase in effectiveness to air leakage from the supply side to the exhaust side, due to the frost blocking the matrix. A schematic of the air leakage caused by frost blocking the matrix is shown in Fig. 20.

7.4. Surface treatment effect

Different shapes of matrices constructed with aluminum, plastic or synthetic fibers are used in regenerative wheels. The matrix may or may not be coated with a desiccant. Coating of the matrix with a desiccant is required for moisture transfer. Without this coating, the equipment is called a heat wheel, as it can transfer only sensible heat if no condensation happens in the wheel.

Experimental testing and theoretical analysis on frost formation in energy wheels with hygroscopic surfaces by Ruth et al. [47] is considered as the very first work in this topic. Moisture was transferred in the case of a non-hygroscopic matrix when condensation occurred in the exhaust air, while in the case of a hygroscopic surface, moisture was transferred even without condensation.

Surface treatment of energy wheels was investigated numerically by Holmberg [25], where two types of surfaces were considered, one hygroscopic and one non-hygroscopic. The non-hygroscopic surface was made of untreated aluminum, while in the hygroscopic case, an oxide layer was formed on the aluminum surface. He found that the time it took for a 50% increase in the pressure drop in hygroscopic wheels was twice that for non-hydroscopic wheels under similar inlet conditions. In addition, the results of Simonson and Besant [43] presented previously indicate a considerable effect of the desiccant type on the latent effectiveness and frosting limit.

7.5. Frost detection methods

One of the most accurate methods to find frosting in an exchanger is visual observation. Due to complexity of the designs, however, observation of frost is not usually practical in most exchangers. Thus, measurement of the air stream properties and performance of the exchanger are generally used to determine when frost forms inside the exchanger. The pressure drop across an exchanger has been suggested in the literature as a reliable factor in determining the presence of frost in exchangers, and in some cases the amount of frost as well [51]. Ruth et al. [47] suggested using a pressure activated switch as a simple and economical means of frost detection and control. Holmberg used pressure drop measurements to compare the performance of exchangers under very cold supply air. Measurement of the effectiveness of an exchanger is another parameter that can be used to determine when frosting occurs. Gazi and Simonson [50] used this method for energy wheels and compared the results with the pressure measurement technique. They found blockage of the air channels increased the leakage between the two air streams resulting in an increase in apparent effectiveness due to frosting where other researchers found that the effectiveness decreased with frosting. Gazi and Simonson concluded that pressure drop was a more reliable parameter in frost detection.

In the laboratory test on an energy wheel under frosting in [51] the average frost thickness was calculated from the pressure drop, as a function of time. Although the average pressure drop increased with time, high fluctuations in the instantaneous pressure drop were observed during 2–4 min cyclic periods, which was a consequence of frost growth and frost fracture. The magnitude and period of these fluctuations increased with time until a specific time. Although pressure monitoring is the best practical method for detection of frost, as described in [11], it is not as accurate as visual techniques. Thus, new techniques or new correlations are required to accurately relate the change in pressure drop to the mass fraction of frost in an exchanger.

A comparison between sensible heat exchangers and energy exchangers is presented in Table 1. In this table, heat exchangers are considered as the reference energy exchangers are compared

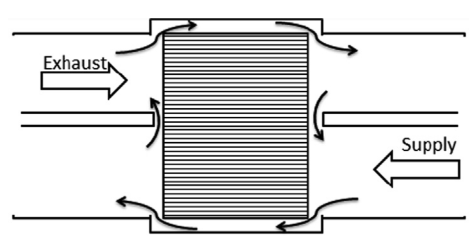

Fig. 20. Cross-leakage in energy wheels with frost blocking the matrix.

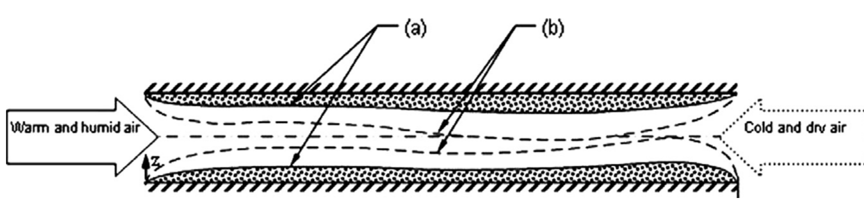

Fig. 19. Schematic of frost thickness in the numerical model by Shang et al. (a) after first frost fracture, (b) just before the frost fracture [51].

Table 1
Qualitative comparison between heat and energy exchangers.

	Energy				Cost implication	Environment
	Frosting limit (temperature)	Sensible effectiveness	Latent effectiveness	Defrosting time	Material and construction	IAQ
Heat exchanger	↔	↔	NA	↔	↔	↔
Energy Exchanger	↓	↔	↑	↓	↑	↑

↔: Reference value; ↑: more than reference value; ↓: less than reference value.

with the reference. Energy exchangers generally have higher capital costs, but have higher energy savings, which can result in lower life cycle costs.

8. Defrosting techniques

Due to the transient nature of the frosting process, it is evident that control strategies for exchangers in cold climates based on a fixed freezing point or a fixed time are inappropriate and may be detrimental to the equipment. A life-cycle analysis of using heat exchangers in cold regions was reported by Nyman and Simonson [2]. They found that energy exchangers under frosting conditions have an optimal operating set point below which defrosting techniques should be activated. This set point should be calculated based on the weather conditions, energy source for heating (electricity or gas) and frost control strategy. One of the main goals in most studies on frosting in heat/energy exchangers is to find a suitable way to reduce the negative effects of frost-buildup. If frosting occurs in exchangers for a long period, use of the exchangers may not be economical. Methods for protecting exchangers against frost can be categorized as frost formation prevention or retardation, and frost removal or defrosting. Different defrost strategies in heat pumps have been presented in [52]. However, not all those techniques are practical for air-to-air exchangers. Several defrosting techniques for air-to air exchangers are described by [46,53,54]. Phillips et al. [53] claimed that in a region with mild weather (less than 4200 heating degree days), no considerable difference was observed between different frost control strategies; while in the very cold regions the differences were noticeable. In the following section, common methods of defrosting are described.

8.1. Preheating the inlet air

Preheating the supply or exhaust inlet is a simple technique to reduce or prevent frosting. Some heating elements are placed in the air ducts, before the entrance of the exchanger. When the outdoor temperature goes below the frosting threshold, the heating elements are activated. To prevent frost formation, the inlet (supply or exhaust) temperature should always be higher than the frosting limit. Another control strategy is to use a pressure drop across the exchanger core to activate the defrosting cycle [12]. In addition to air-to-air heat exchangers, preheating the air has been reported for heat pumps [55]. The disadvantage of preheating the inlet air in very cold regions is that it reduces the energy recovered by the energy exchanger considerably [13]. A comparison of different frost protection strategies shows that preheating the supply air is not economical in regions with long periods of cold temperatures [24,53].

8.2. Reducing the supply airflow rate

This technique is used to remove frost that has formed inside an exchanger. In this method, the supply airflow rate is decreased, while the exhaust airflow rate remains unchanged. Kragh et al. [13] monitored the exhaust flow rate and effectiveness of a counter-flow plate heat exchanger with this technique for a single-family house and in a laboratory test. Frost protection was activated for exhaust air outlet temperatures below 3 °C and deactivated at 5 °C. In the field test, the flow rate started to decrease after 2 h of the exchanger working with a supply temperature of −5 °C. The disadvantage of this technique is that it is not useful for long periods, since running the exchanger with an unbalanced flow rate would increase infiltration in the building. Tommerup et al. [56] found a similar problem when they used this method for a single family house.

A sensitivity study was done by Nyman and Simonson [2] on the frost control system set point temperature. Closing the supply side, while the exhaust side remained open was selected as the defrosting technique. They considered three different set points for the exhaust outlet temperature, −30 °C (no frost control), 5 °C, and 10 °C. They found the difference in the recovered energy for the first two set points was 2–4%, but for 10 °C the recovered energy decreased by 12% compared to the two other set points. Therefore, they suggested 5 °C as optimum frost control temperature.

Preheating or reducing the supply air flow rate was used by Fisk et al. [12] in testing a counter-flow and a cross flow heat exchanger. The defrosting time fraction (time required to defrost over total elapsed time) was found to be dependent on the duration of each cycle, as well as on the outside temperature and indoor air conditions. The average defrosting time fraction was found to be more for counter-flow exchangers compared to the cross-flow model. Therefore, from an energy savings point of view, using a counter-flow exchanger when frosting is likely to occur for a significant fraction of the year has no advantages over a cross-flow exchanger. In addition, full blockage of the air streams in cross-flow exchangers is less likely to occur, which was confirmed in experiments by Fisk et al. [12].

8.3. Recirculating warm exhaust air

In this technique, ventilation is stopped temporarily, and indoor air is recirculated through the exchanger to melt the frost. This method is similar to the two previous methods; however, no outdoor air enters the building (through ventilation or by infiltration). A comparison of defrosting techniques by Phillips et al. [53] showed that this technique is most suitable for extremely cold climates. Warm air recirculation was utilized in designing a residential building in an arctic area in [38]. It was recommended that the defrosting time should not exceed 20% of the total operational time. Their control system was activated when the supply air outlet temperature went below 1 °C and deactivated when the temperature went back to 4 °C. When recirculating the warm indoor air, increasing the fans speed causes more heat transfer from the fans into the circulated air, which enhances melting [14].

Defrosting by recirculating warm exhaust air and shutting off the supply air was suggested by [40] as a defrost method in plate heat exchangers with supply air temperatures between −20 °C and −40 °C. It was recommended to run a 4–5 min defrosting cycle after every 40 min of working time. A lack of empirical correlations for frosting and no experimental data to validate the results are the main limitations of [40], on the other hand in [12], experimental results were provided in which preheating or shutting off the supply airflow

was suggested as the two main defrosting techniques. The difference between the two methods, in practical applications, is that with preheating, the operation of the exchanger is not interrupted. Fisk et al. found that 6–26% of the heat exchanger operational time was used for defrosting under supply air temperatures of −12 to −20 °C. A more detailed calculation for defrost time under a variety of outdoor temperatures was provided in [38] along with a life-cycle cost analysis for a heat exchanger with warm air recirculation as the defrosting method in residential houses that showed a payback period of seven years. Ninomura and Bhargava [38] recommended using frost protection technique for temperatures below −4 °C. Defrost cycle duration was calculated around 13% for supply temperature below −4 °C and 22% for temperatures below −25 °C by warm exhaust air recirculation.

8.4. Bypassing the supply air

In this technique, all or part of the supply air is bypassed around the exchanger, into the supply outlet, while the exhaust airflow rate remains unchanged, as seen in Fig. 21. In some cases, a moisture adsorbing system is incorporated when the exhaust air is passing thorough the exchanger to adsorb moisture and pass it into the supply air [14]. The amount of supply air that is bypassed around the core is controlled by the set point temperature or pressure drop in the exhaust side. Although no air leakage problems are observed, an unbalanced airflow through the exchanger would decrease the energy transfer rate of the exchanger considerably [9]. Heat recovery units are typically equipped with a bypass, which is used to move the airflow around the heat exchanger. Because of its simplicity and high reliability (in removing frost), this technique is also used in the air-conditioning systems on airplanes [10]. In these systems, one third of the cold air should be bypassed when the temperature goes below −8 °C.

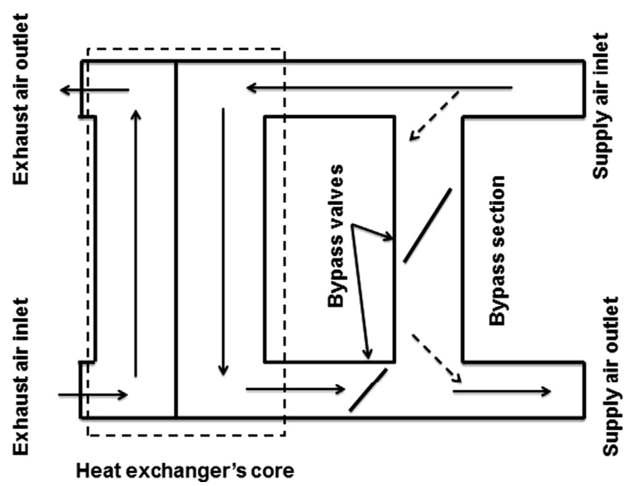

Fig. 21. Schematic of a bypass system in an exchanger [9].

8.5. Reducing the effectiveness of the exchanger

Reducing the effectiveness of an exchanger will decrease the risk of frost formation because the warm and humid exhaust air is not cooled as much. Effectiveness can be decreased by changing the working conditions of the exchanger. In heat pipes this can be done by tilting the pipes, and in energy wheels this can be done by changing the wheel speed [8]. This technique has been suggested by some companies [46] and has been investigated by several researchers [25,43,47]. Holmberg [25] suggested reducing the exchanger effectiveness until the pressure drop returns back to preset values. Simonson and Besant [43] used this method for different desiccant types in energy wheels. To choose an economical defrosting technique, the time required for defrosting is important, because if the time is small it may be more economical to shut down the wheel completely, rather than reducing the speed. Ruth et al. [47] found that with lower exchanger effectiveness or when the indoor RH was lower, frosting was less likely. Ruth et al. used a very simple model, but it was useful in the estimation of the frosting limit of energy wheels. By knowing the temperature limit, it was easy to estimate the total time before frosting would occur in an energy wheel in a cold season.

8.6. Auxiliary exchanger or double core heat exchanger

In this technique, two separate exchanger cores are considered as one system, as seen in Fig. 22. When frost build up increases the pressure drop or decreases the flow rates from a set limit, a control

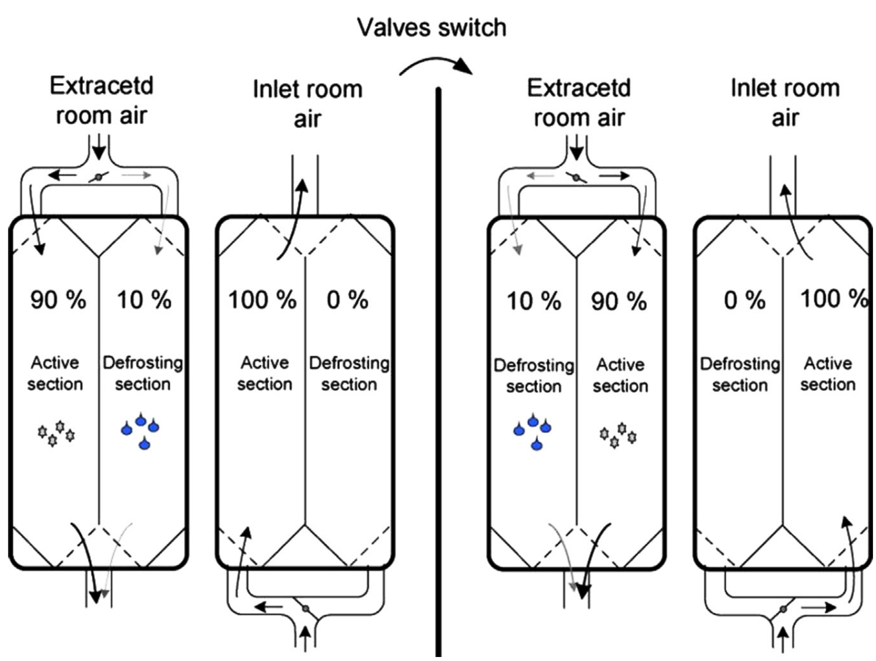

Fig. 22. Schematic of an auxiliary exchanger or double core heat exchangers [57].

system distributes the supply and exhaust air to the second core, while part of the exhaust air (10%) is used for melting the frost in the main core. The time between section switch was 30–60 min spending on the flow rate. Kragh et al. [57] tested this system under −6 °C supply air temperature, and found that the increase in pressure drop deactivated the system after 23 h when the defrosting cycle was off. On the other hand when the defrost cycle was activated no considerable change in the effectiveness and flow rate was observed during 24 h test. Advantages of this system are that the pressure drop is low, and it has a simple construction, but a disadvantage is that its size is bigger than other exchangers with similar capacity. Numerical modeling of this system was presented by Nielsen et al. [42]. Although, good agreement was observed for the frosting process, results deviated from the experiments during the defrosting cycle. Nielsen related the source of this difference to neglecting the effects of natural convection, and poor measurement methods in the experiments. Due to a lack of experimental results under very cold temperatures, the performance of the system in very cold climates is uncertain.

8.7. Coating on the surface of energy wheels

The use of different types of coating on the surface of energy wheels is being given more attention, since coating and desiccant technology is an important parameter in rotary energy exchangers. If the moisture adsorption capacity of the wheel is increased, less frosting will be observed [43,58]. A parametric study done by [15] showed that a hydrophobic coating on the aluminum surface has no effect on frosting (rate of growth or location),while a hydrophilic coating can hinder the formation of frost. Frost free time, the time during which no frost was observed on the surface, was used to compare the effects of the different coatings. Parameters affecting the frost free time were temperature, RH and coating thickness. Although, the frosting limit did not change, experiments have shown that frost free time increased considerably as the coating thickness increased [15]. A drawback of using a hydrophilic coating is the disappearance of anti-frosting properties after three cycles of frosting-defrosting [15]. Liu et al. [59] studied effect of coating on frosting on fin-tube-heat exchangers surface. Similar to [15], they found that the frosting limit did change with the type of coating, however a thicker coating resulted in a higher pressure drop in the exchanger due to a reduction in active space for the airflow. Contrary to [59] and [15], Wang et al. [60] found that hydrophobic surfaces can retard the frosting process. Although frost free time did not change much in a horizontal orientation, no frost was observed in a vertical orientation when the surface temperature was −7 °C on super hydrophobic surface [60]. One advantage of this surface over the hydrophilic surfaces was the stability of frost free properties of the surface when repeating the experiments.

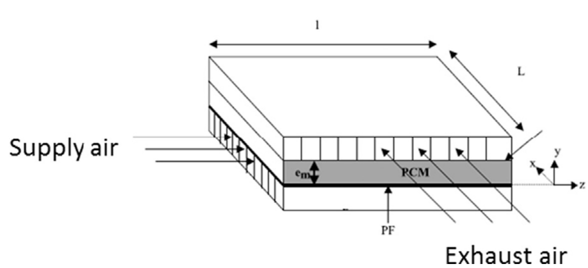

Fig. 23. A cross flow heat exchanger with PCM [61].

8.8. Phase-change materials

Although much work has reported on modeling and measuring the performance of heat exchangers under frosting conditions, none of previously cited works considered the thermal capacity of the separating walls between the airstreams. Using phase-change materials (PCM) on the separating walls inside the exchanger was suggested by Qarnia et al. [61] A cross-flow heat exchanger with PCM on the separating walls is shown in Fig. 23. In this technique, the exhaust air surface is kept above the freezing point by utilizing PCM and electrical heating elements. The effects of electrical load and Biot number (proportional to the ratio of PCM thickness over the PCM thermal conductivity) for the PCM layer were investigated numerically and experimentally for this type of exchanger. Qarnia et al. [61] found that increasing the electrical heating or Biot number improved the frosting limit of the exchanger, while increasing the heating energy decreased the efficiency of the exchanger (not effectiveness). A drawback for this system is the lack of experimental results to prove applicability of this system under very cold supply air.

8.9. Moving belt and rollers

This technique, which is designed to partially close the supply air channels of cross-flow plate heat exchangers, was invented by Hallgren [62]. In this system, a device consisting of a belt and rollers is mounted on a moving frame and is used to cover some of the supply air channels of the exchanger, as shown in Fig. 24. The warm exhaust air continues to flow in the adjacent channels, causing the frost that has formed to melt. The advantages of this system are continuous defrosting without considerable change in effectiveness and pressure drop, and the possibility of removing

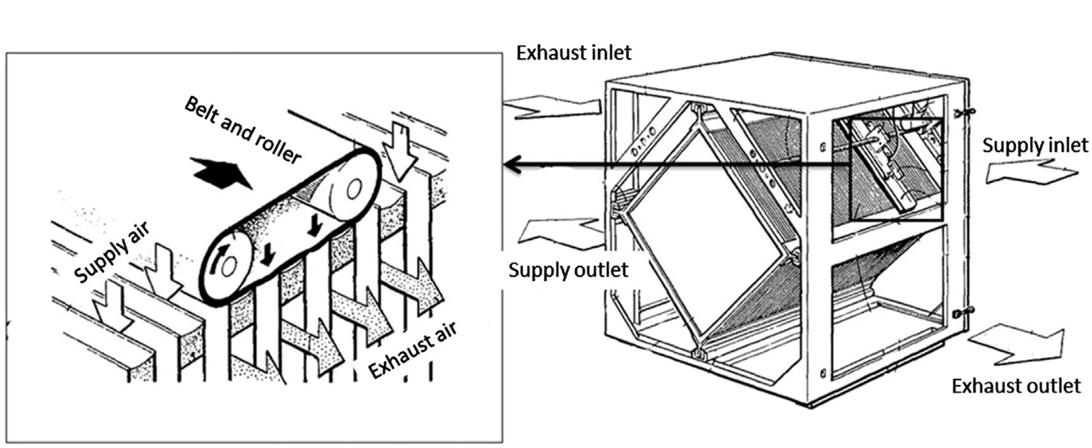

Fig. 24. Defrosting system by Hallgren to partially block supply air channels [62].

Table 2
Frost control strategies or defrosting techniques in air-to-air heat/energy exchangers.

Technique	Control parameter	Capital cost	Operating cost	IAQ	Advantages	Disadvantages
Preheating the inlet air [12,13,24,53]	Air temperature	↔	↑	↔	Simple; Can be used as frost prevention	Not economical in regions with long cold seasons
Reducing or closing the supply air side [2,12,13,56]	Flow rate	↔	↔	↓	Simple	May decrease IAQ. Increases infiltration to building;
Recirculating warm exhaust air [14,38,53]	Flow rate	↔	↔	↓	Simple; Melting process can be enhanced by increasing flow rate; suitable for extremely cold climates.	No outdoor ventilation air during defrosting
Bypassing the supply air partially or fully [9,10,14]	Flow rate	↔	↑	↔	Simple	Reduced energy recovery during defrosting
Reducing the effectiveness [25,43,46,47]	Rotational speed of energy wheel, Tilting angles in heat pipes	↔	↑	↔	Simple; Can be used as frost prevention	Longer defrosting time than other techniques; not applicable in plate heat/energy exchangers; reduced energy recovery during defrosting
Auxiliary exchanger or double core heat exchanger [42,57]	Flow rate	↑	↔	↔	one exchanger provides energy recovery while other exchanger is defrosted	increased capital cost for large or redundant exchanger; not enough experimental results are available under very cold temperature
Changing surface properties [15,43,58–60]	Coating type and thickness, membrane permeability	↑	↔	↔	appropriate materials may significantly reduce the frosting limit	Depend on many parameters each design is different; uncertainty in material long-term performance and durability
Use of phase-change materials [61]	Surface temperature	↑	↔	↔	Continues high performance running	Not enough experimental results are available under very cold temperature; difficult design and control system
Partial blockage of supply inlet [62]	Flow rate	↔	↔	↔	Continues high performance running	The amount of the blockage or moving speed of belt and roller depend on operating conditions.

↔: No considerable change; ↑: Increase; ↓: Decrease.

frost in select channels. This is important, since frosting may occur in different areas of the core of cross-flow heat exchangers. However, unbalanced flow rates in the exchanger for long periods will depressurize the building, which will lead to an increase in infiltration.

8.10. Design and installation of exchangers

In addition to defrosting or frost protection techniques, which are important in order to keep the effectiveness of an exchanger high in cold climates, appropriate installation (location and orientation) of the exchangers is also important. Knowing that condensing water vapour is the main source of frost, exchangers should be designed in a way to remove the condensation before it freezes. Installing the exchangers so that the exhaust airflows upward, would help the condensation run off the warm side of the air channels. In addition, when frosting is a problem, installing the exchanger in a heated room (such as a utility room) is preferred to an unheated room (such as an attic) [56]. Chichindayev [10] suggested some new modifications to the design of exchangers to keep the surface temperature above zero. To achieve this, Chichindayev tried to keep the thermal resistance of the cold air passage higher than that of the warm air. Two suggestions were to reduce the airflow velocity by increasing the number of air channels, and the second was to use a multiple-pass exchanger. Chichindayev found that increasing the number of passes lead to a more favorable temperature distribution on the exchanger's surface that kept the exhaust air channels above the freezing point. However, the effectiveness of this new design was not compared with typical design.

A summary of the frost control strategies discussed is presented in Table 2. Capital cost, operating cost, and IAQ for each technique were compared with the same exchanger without defrosting cycle. It should be noted that in most strategies the duration of the defrosting cycle depends on the inlet conditions.

9. Conclusions

This paper reviews open literature in the field of frosting in air-to-air heat/energy exchangers. The concept of frost formation in exchangers has received increasing interest from researchers and industry over the past 30 years. Several papers were described that studied formation of the frost layer and measured the frost properties such as density, thermal conductivity and roughness. The unsteady process of frosting makes it difficult to get a general conclusion about these properties or develop a specific correlation to accurately predict frost properties. Based on the literature review in this paper, the following conclusion on frosting in air-to-air heat/energy exchanger can be made:

- blockage of the air channels by frost decreases the exchanger's effectiveness considerably. Providing an equal frost deposition pattern would delay blockage,
- moisture transfer in energy exchangers decreases the frosting limit,
- most of the available results for energy exchangers are presented for energy wheels,
- energy wheels with hydroscopic surfaces have lower frosting limit compare to non-hydroscopic wheels,
- of the different method available to detect frost (temperature and effectiveness monitoring, pressure drop measurement, visual inspection) pressure drop monitoring is the most reliable technique, if no visual technique is possible,
- one advantage of hydrophobic surfaces over the hydrophilic surfaces was its stability to retain frost free properties after repeated testing,
- although, the frosting limit did not change, experiments have shown that hydrophobic can retard the frosting process. In some other cases hydrophilic surfaces was suggested to improve frosting limit. Thus, no general conclusion can be drawn thorough the literature for the effect of coating on frosting.

- Defrosting or frost protection techniques were described. However, with all of these techniques, a portion of the recovered energy would be sacrificed or the capital cost would be increased, which makes the techniques impractical in certain cold conditions,
- it can be reported that few innovative techniques for frost protection have been presented in the last fifteen years. Such as exchangers with PCM, auxiliary exchangers.

Important topics that have not been covered in the literature, based on the presented statistics and the literature review are:

- no work (numerical or experimental) has been reported on frosting in membrane-based energy exchangers,
- few numerical models were reported that considered the effect of frost accumulation on the airflow rate in energy wheels and plate heat exchangers,
- very few new defrosting techniques for air-to-air heat/energy exchangers have been presented in the last 15 years and
- very few studies have considered supply air temperatures less than $-20\ ^{\circ}C$.

In general, the problem of frosting in air-to-air heat/energy exchangers is still unresolved, and specifically, more work is needed to study frost in exchangers which transfer latent heat as well as sensible heat. Some discrepancies in results, new surface materials, and different cooling and heating techniques would suggest new interesting areas for future work for researchers. In addition, more research is required to find new defrosting techniques or frost prevention methods to improve the performance of heat/energy exchangers under all outdoor conditions.

Also, most of the literature focused on changes in effectiveness, pressure drop or time of defrosting. However, the effect of frosting on energy consumption would depend on the exchanger design, working condition and defrosting technique. This effect is one area that is lacking in the literature and an area of future work.

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